

Auditory Masking Patterns in Bottlenose Dolphins from Anthropogenic and Natural Sound Sources

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LONG-TERM GOALS

The long-term goals of this project are to better understand and predict auditory masking in odontocetes with realistic, environmental noise types. Current predictions based on Gaussian noise will be improved upon.

OBJECTIVES

The objectives of this effort are to understand and predict how environmental noise (both anthropogenic and natural) affects detection, discrimination, and recognition abilities of odontocete cetaceans. The specific objectives for FY11 were to:

- Estimate masked *detection* thresholds (i.e., critical band procedure) with different noise types.
- Begin estimating *discrimination* and *recognition* thresholds with different noise types.

Future objectives for FY12 are to:

- Complete estimating *discrimination* and *recognition* thresholds with different noise types.
- Develop and test hypotheses to describe the auditory processing governing the resulting masking patterns, and
- Develop predictive quantitative models to describe masking with environmental noise.

APPROACH

Critical ratios (CRs) derived from laboratory masking experiments, which utilize Gaussian noise, are typically used to predict the amount of auditory masking in real marine environments. If the pressure spectral density of noise (L_N) and the CR of an animal are known, the signal level (L_S) at threshold is assumed to be:

$$L_S = CR + L_N$$

where L_S uses the reference pressure of 1 μPa and L_N use the reference of 1 $\mu\text{Pa}^2 / \text{Hz}$.

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The use of the critical ratio is restricted by the assumption that environmental noise is Gaussian and auditory masking is restricted to noise within a single auditory filter centered on the signal frequency. Recent marine mammal masking studies with non-Gaussian noise maskers have demonstrated that this assumption does not generalize to all environmental noise types (Branstetter and Finneran, 2008; Erbe, 2008; Trickey et al., 2011). For non-Gaussian noise types such as snapping shrimp and comodulated noise, the auditory system utilizes the temporal pattern of noise, across multiple auditory filters to segregate the signal from the noise, resulting in enhanced signal detection capabilities (Branstetter and Finneran, 2008). Environmental noise, both natural and anthropogenic, may also be non-Gaussian, resulting in masked detection thresholds that are not predicted from CRs. The primary goal of the current project is to better understand auditory masking by determining masking patterns for a broad variety of environmental noise types and define the mechanisms that govern auditory signal processing in environmental noise.

Study 1. Masked detection thresholds for a pure tone in complex noise

Behavioral detection thresholds were measured using an up/down adaptive staircase procedure (Levitt, 1971). The method for estimating masked thresholds is identical to a standard behavioral hearing test except masking noise is played continuously during the threshold estimation procedure. A band-widening technique (i.e., critical band procedure) was used which estimates thresholds as a function of noise bandwidth. For a 10 kHz tone signal, noise bandwidths were 0.10, 0.25, 0.5, 1, 2, 4, and 8 kHz. One of the primary advantages of a band-widening paradigm over a critical ratio paradigm (tone detection in broadband noise) is that the pattern of masking can reveal clues to the type of auditory processing taking place.

In addition to noise samples recorded in San Diego Bay, we have collaborated with Marc Lammers and Jennifer Miksis-Olds (Award number N000140810391) who have provided us with field recordings of noise found in marine mammal environments. Field recordings include natural biological sounds (snapping shrimp, humpback whale song, pinniped chorus, whale social sounds), natural non-biological sounds (rain, ice-squeaks) and anthropogenic sounds (pile saw, motor boat noise, C-tractor tug boat, vibratory hammer, seismic airgun, vessel echo-sounder). Of these sounds, Humpback whale, pinniped chorus, whale social sounds and C-tractor sounds were rejected because most of the spectral energy was below typical communication signals of odontocetes. Transient sounds (seismic airgun, vessel echo sounder and vibratory hammer) were also rejected because their short durations would only mask a small temporal portion of the 500 ms signal). The remaining noise types used in the experiment are presented in Table I. All noise types were filtered to produce a flat spectral density (95 dB re 1 $\mu\text{Pa}/\text{Hz}$) after being projected from a Reson ITC 1001 transducer.

Table 1

Noise type	duration	sampling rate
boat noise (BT)	60 sec	44.1 kHz
pile saw (PS)	30 sec	96.0 kHz
ice squeaks (IS)	5 sec	100.0 kHz
rain (RN)	15 sec	40.0 kHz
snapping shrimp (SS)	3 min	96.0 kHz
Gaussian (UC)	3 min	44.1 kHz
comodulated (CM)	3 min	44.1 kHz

All noise types were looped continuously and presented at flat spectrum level of 95 dB re 1 $\mu\text{Pa}^2/\text{Hz}$.

Study 2 Masked detection thresholds for complex signals in complex noise

The methodology of Study 2 was similar to Study 1, however instead of a pure-tone signal, seven complex signals were used. Figure 1 displays recorded phonations (whistle, burst-pulse, and clicks) from the dolphin SAY that were used as signals. Each signal was band pass filtered (8 kHz to 12 kHz) and the noise bandwidth was held constant (6 kHz to 14 kHz). Four noise types were selected (CM, UC, SS, and IS) that resulted in the greatest divergence in masking patterns from study 1. Study 2 also incorporated four synthetic signals (frequency modulated tones) that were intended to be a more controlled odontocete whistles analogue (see figure 2).

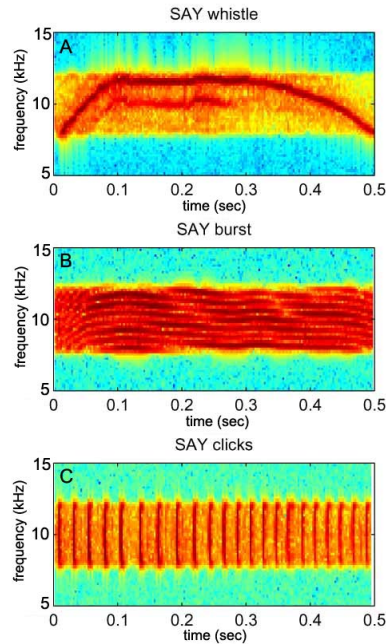


Figure 1. Phonations recorded from the dolphin subject SAY used in a detection threshold experiment. A) whistle, B) burst-pulse and C) click train. Each phonation was band pass filtered (8 kHz – 12 kHz followed by a correction filter to produce a flat spectral density level.

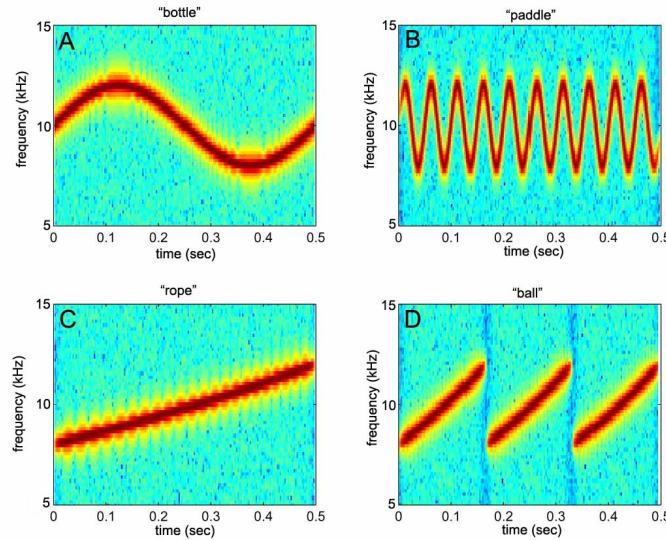


Figure 2. Synthetic whistle stimuli used to measure detection, discrimination and recognition thresholds. Each signal will be paired with an arbitrary object (e.g., A is paired with a rope, and B is paired with a paddle) for masked recognition thresholds.

Study 3. Comparison between detection, discrimination and recognition thresholds in complex noise

Noisy environments have the potential to not only compromise an animal's ability to detect a signal, but can also interfere with an animal's ability to discriminate or recognize important features of signals. Specific communication signals in marine mammals likely serve specific functions including mating displays, fighting assessment, recognition of group members and individuals, maintaining group cohesions, and maintaining individual social relationships (Tyack and Clark, 2000). Masking noise will interfere with these functions if the animal is not able to recognize key features of a signal.

For estimating masked *discrimination* thresholds, an alternating sound task (Dooling and Okanoya, 1995) was used. A dolphin was presented with a repeating 500 ms frequency modulated (FM) signal (from figure 2). If the FM signal changed to a different FM signal, the dolphin was trained to whistle indicating it was able to discriminate between pair. If the signal did not change, the dolphin was trained to remain silent (catch trial). All paired comparisons were presented at equal sensation levels (SL) to ensure discriminations were based on the frequency contour of the signal and not the level of the signal. Signals from figure 2 were used in this experiment. An adaptive stair case procedure was used to titrate the level of the signal pairs, and estimate discrimination thresholds in the presence of continuous noise. All noise had a flat spectral density of 95 dB (re 1 $\mu\text{Pa}^2/\text{Hz}$), band pass filtered between 6 and 14 kHz. The noise types from Study 2 were also used in this experiment.

For estimating recognition thresholds, a differential response will be associated with each of the four sounds in figure 2. For example, when the sound in figure 2A is presented to the dolphin, the dolphin will swim and touch an aluminum bottle. If the sound in figure 2B is presented, the dolphin will swim and touch a paddle. Each sound will have a different semantic component or meaning. As in the previous masking paradigms, masking noise (same level and bandwidth as discrimination study) will

be played continuously while the level of the signals will be adjusted to determine masked *recognition* thresholds.

Key personnel in this effort have been Brian Branstetter Ph.D. (PI) who participated in all aspect of this study. Jennifer Trickey (research assistant) helped with data collection. Several dolphin trainers aided in the training of the dolphin and data collection of this project. James Finneran Ph.D. Dorian Houser Ph.D. and Jason Muslow Ph.D. helped develop custom Labview software, and aided in experimental design.

WORK COMPLETED

Masked detection thresholds in complex noise

Detection thresholds for a 10 kHz tone embedded in seven different noise types (from Table 1) were completed. For each noise type, seven bandwidths were used as maskers. Four replicates at each condition (noise type and bandwidth) were collected and averaged to determine masking patterns.

Detection thresholds were also measured for the signal types in Figure 1 and Figure 2. This required Labview software development (by James Finneran) that could estimate thresholds using an adaptive staircase procedure with any arbitrary wavefile for the signal. Four noise types were chosen based on diverging masking patterns (see Results). Four replicates at each condition were collected and averaged.

Masked discrimination thresholds in complex noise

A dolphin was trained to perform the alternating sound task (Dooling and Okanoya, 1995) using the synthetic whistle stimuli (figure 2, signals A-D). These stimuli were chosen because detection thresholds were nearly identical (see results). Custom Labview software was developed (Jason Mulsow) to control stimulus generation and the data collection procedure during this task. Discrimination thresholds were estimated (four replicates for each condition) where each signal type was compared to all other signal types.

Masked recognition thresholds in complex noise

Training is in progress for this experiment using the same dolphin (SAY) that participated in the previous studies.

RESULTS

Masked detection thresholds for a pure tone in complex noise

Figure 3 displays masking patterns for a 10 kHz tone in different noise types. All of the noise types demonstrate an increase in thresholds as a function of bandwidth up to approximately 1 kHz (the critical bandwidth at 10 kHz). After 1 kHz, there is a processing transition where masking patterns of different noise types begin to diverge. Boat noise and rain, were generally within 5 dB of the Gaussian noise masking pattern. Pile saw and ice squeaks displayed consistently elevated thresholds compared to Gaussian noise while snapping shrimp and comodulated noise displayed lowered thresholds consistent with comodulation masking release.

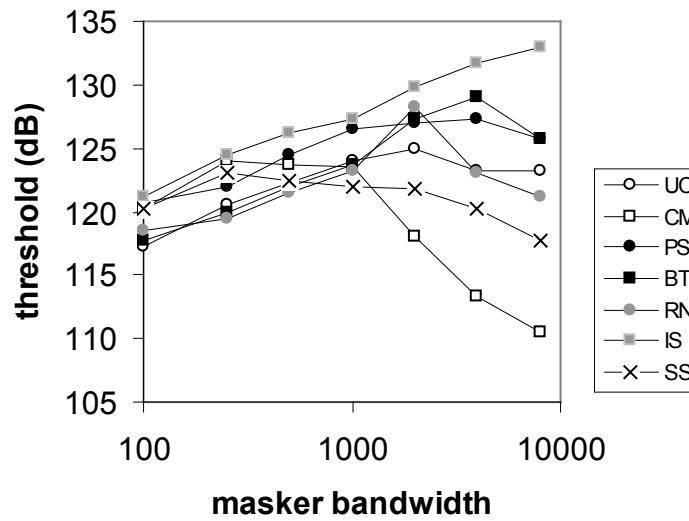


Figure 3. Masking patterns for different noise type (UC=Gaussian, CM=comodulated, PS=pile saw, BT= boat motor cavitation, RN = rain, IS=ice squeaks, and SS=snapping shrimp. Each data point is the average of 4 thresholds. Error bars have been omitted for clarity but the standard deviation for each data point was < 3 dB. Masking patterns are similar for bandwidth up to 1 kHz. Masking patterns diverge for bandwidths greater than 1 kHz suggesting a processing transition.

Masked detection thresholds for complex signals in complex noise

Figure 4 illustrates detection thresholds for a variety of signal types with different noise maskers. Whistles, burst pulse, and synthetic whistles (A-D) all have masking patterns that are similar to the results from Study 1 which used a pure-tone signal. The major exception was the masking pattern for the “clicks” signal. With clicks, there was no release from masking with comodulated noise. Snapping shrimp noise resulted in elevated thresholds, and there was a release from masking with ice squeak noise.

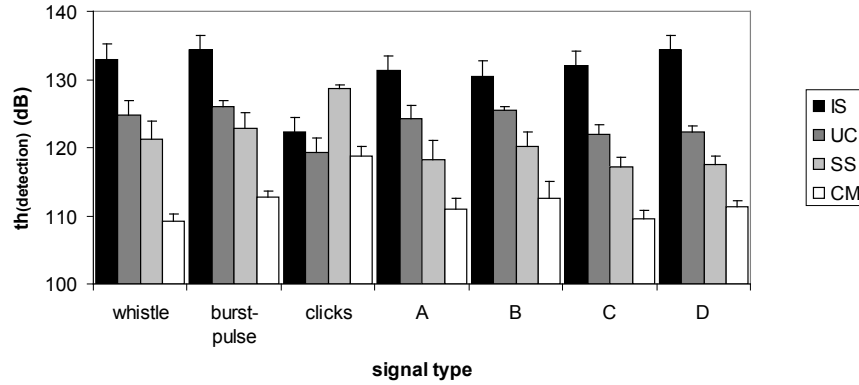


Figure 4. Masked thresholds for the seven signal types (see figures 1 and 2 for descriptions of the seven signals), with four noise types. Masking patterns were similar for all signal types except clicks. Error bars represent standard deviations.

Masked discrimination thresholds in complex noise

Figure 3A illustrated masked discrimination thresholds from study 2. Figure 3B illustrates the difference between detection and discrimination thresholds defined by:

$$\Delta S = S_{\text{dis}} - S_{\text{det}}$$

Where S_{dis} and S_{det} are the discrimination thresholds and detection thresholds (in dB re 1 μPa) respectively. Most discrimination thresholds are within 2 dB of detection thresholds except for signals masked by ice squeaks (IS). Discrimination thresholds for ice squeak noise are actually less than detection thresholds which is a counterintuitive and unexpected result.

IMPACT/APPLICATIONS

Masked detection thresholds for a pure tone

For narrow band noise (i.e., noise with a bandwidth less than a single auditory filter) the power spectrum model of masking (Moore, 1993) provides a reasonable description of the data. All noise types demonstrated a monotonic threshold increase as a function of masker bandwidth. However, when noise bandwidths exceed the bandwidth of a single auditory filter, threshold can no longer be predicted by the power spectrum model. The dolphin auditory system appears to use multiple processes that depend on the physical attributes of the noise (e.g., amplitude fluctuations of the temporal envelope across auditory filters). This result is significant and provides evidence that critical ratio predictions for non-Gaussian noise can be considerably inaccurate. A more sophisticated biologically inspired model will be better suited to describe and predict masking patterns for environmental noise and will be part of this project's effort for FY2012.

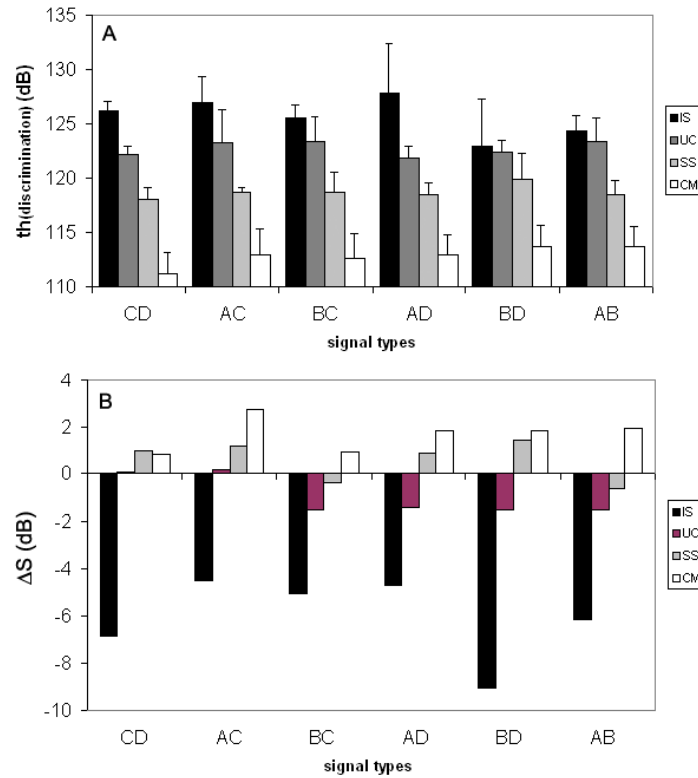


Figure 5. Masked discrimination thresholds (A) between each possible pair of stimuli from figure 2. Threshold differences (ΔS) between discrimination and detection tasks. The signal types on the x-axis represent stimulus pairs. For example, CD are the stimuli “C” and “D” from figure 2.

Masked detection thresholds for complex signals in complex noise

All signals except “clicks” resulted in masked detection thresholds with a pattern similar to pure tones. This result was expected for tonal signals such as the recorded whistle and the synthetic whistles. The masking pattern for “clicks” was distinctly different but not surprising. Noise composed of transient sounds (i.e., snapping shrimp) appears to have a more profound effect masking click like signals. This result is not predicted by the power spectrum model. Surprisingly, burst-pulse signals (which are similar to click signals with a smaller inter-click-interval) produced masking patterns more similar to pure tones than clicks. This suggests burst-pulse signals undergo similar processing as whistle type signals.

Masked discrimination thresholds in complex noise

Masked discrimination thresholds were very similar to masked detection thresholds (typically within 2 dB), with the exception of thresholds estimated in IS noise. Discrimination thresholds with IS noise were lower than detection thresholds which is counterintuitive and unexpected. However, this result can be explained. IS noise, like odontocete whistles, is composed of frequency modulated tonal components. During the detection threshold experiment, the dolphin’s auditory system registered the signal (detection) but the dolphin failed to identify the tone as the signal and thought it was part of the background noise. Thresholds were lower in the discrimination tasks because the sounds had a

predictable repeating pattern (every 600 ms) that cued her when to listen for a potential change. No such cue existed during the detection tasks.

Auditory scene analysis vs. energetic masking

Understanding detection and discrimination abilities with complex signals and complex noise cannot be reduced to understanding the dolphin's sensitivity to simple stimuli such as pure tones and Gaussian noise. The results reported here provided strong evidence that amplitude modulation and frequency modulation are important acoustic dimensions used to segregate one sound from another. Understanding these patterns requires an approach more consistent with analog human studies on auditory scene analysis rather than an energetic masking approach.

RELATED PROJECTS

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